What have we learned from elliptic flow at RHIC ?

Hiroshi Masui / LBNL
NSD monday morning meeting on Nov. 2, 2009

Thanks to
P. Filip, R. Lednicky, B. Mohanty, A. M. Poskanzer, S. S. Shi, A. H. Tang and N. Xu

Main messages

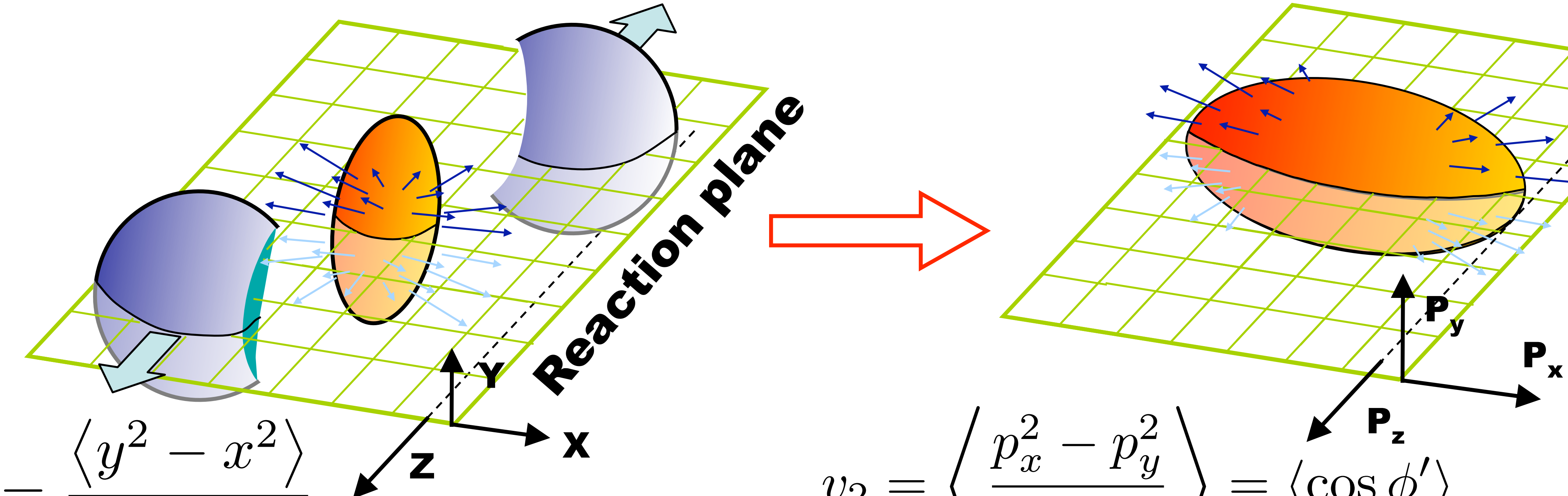
- Create hot/dense medium and understand properties
  - ✓ thermalization
  - ✓ deconfinement
  - ✓ transport coefficients
  - ✓ ...

- Success of hydrodynamical models
- Partonic collectivity
- Stronger collectivity in central collisions
- ‘Viscosity’ corrections

Outline

1. Introduction
2. What have we learned at RHIC ?
3. What can we learn from future v_2 measurements at RHIC ?
4. Conclusions

Why study elliptic flow ?



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos \phi' \rangle$$

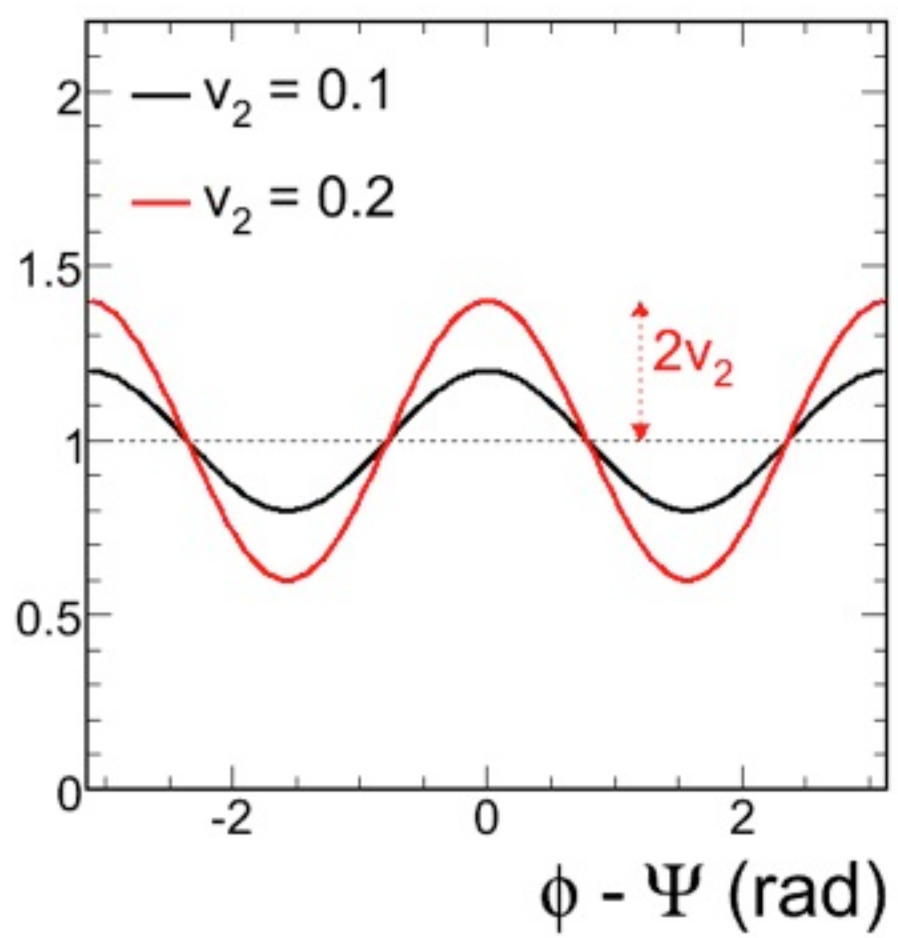
- Initial spatial anisotropy (eccentricity ε) → final momentum anisotropy v_2
  - ➡ Interactions among constituents
  - ➡ Degree of thermalization, EOS, d.o.f, transport coefficients
- Signal is self-quenching with time
  - ➡ Probe to the early stage
- Sensitive to the early 'partonic' collision dynamics

How to measure anisotropic flow ?

$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos(\phi - \Psi_{\mathrm{RP}}) + \boxed{2v_2 \cos(2[\phi - \Psi_{\mathrm{RP}}])} + \ldots$$

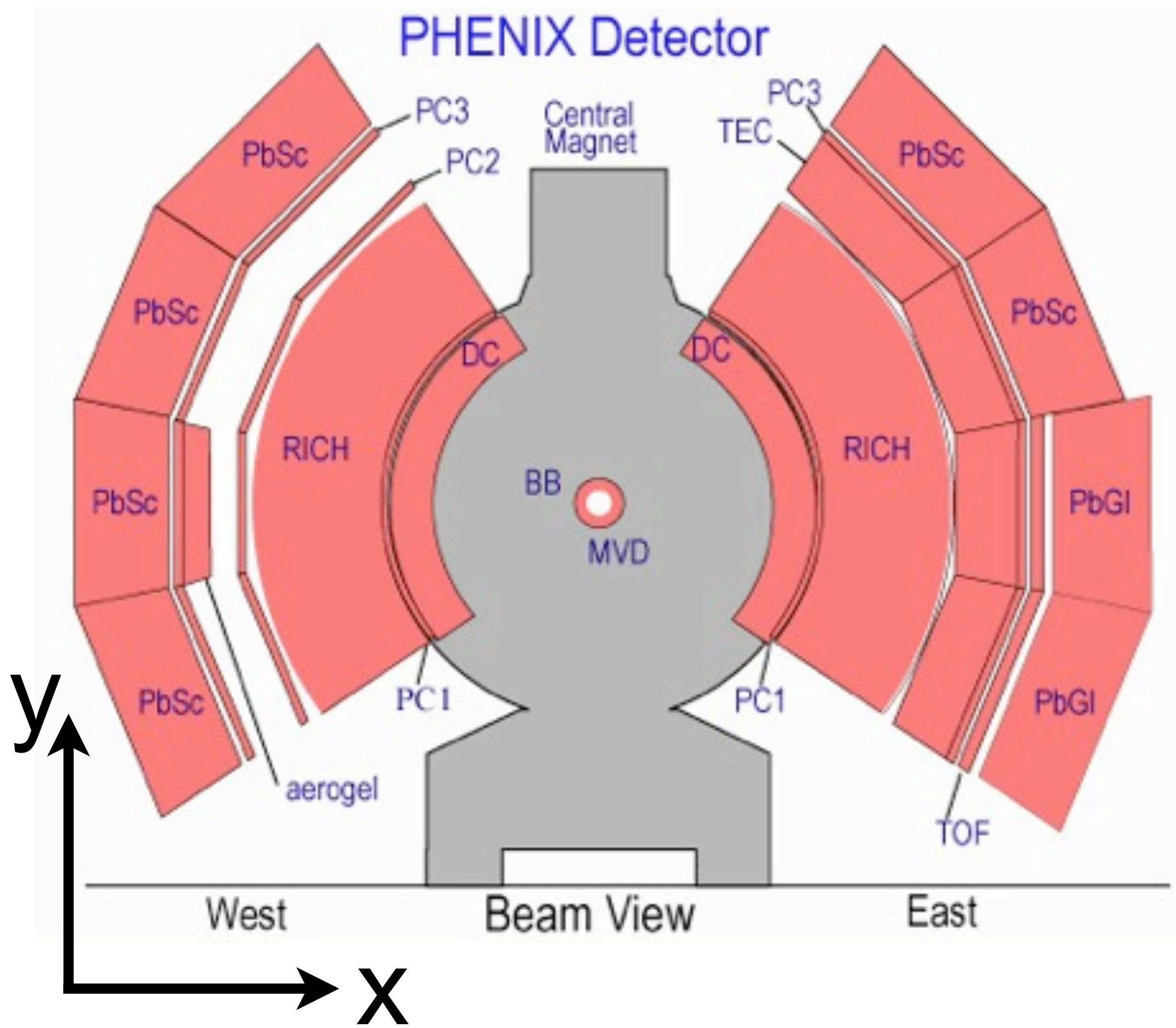
ϕ : azimuthal angle of particles

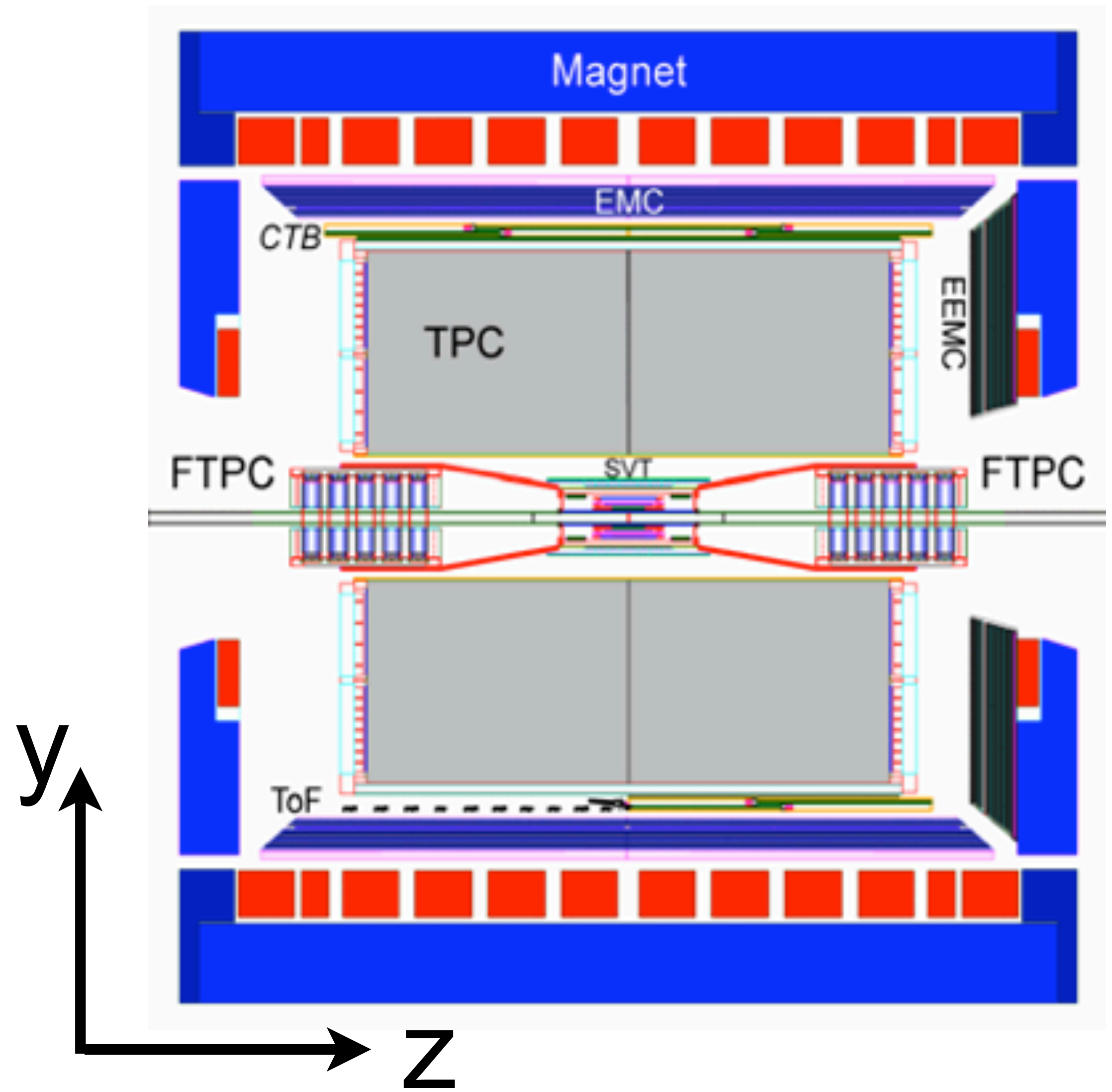
Ψ_{RP} : azimuth of reaction plane



- Azimuthal anisotropy
  - ✓ Fourier expansion of azimuthal particle distributions with respect to the reaction plane
  - ✓ Second coefficient = v_2
  - ✓ v_2 = 0.1 (10%) → 1.2/0.8 = 50% more particles in "in-plane" direction than in "out-of-plane"

PHENIX vs STAR





- Central arm: $|\Delta\phi|<\pi$, $|\eta|<0.35$
- photon, electrons

➡ Limited acceptance, rare probes

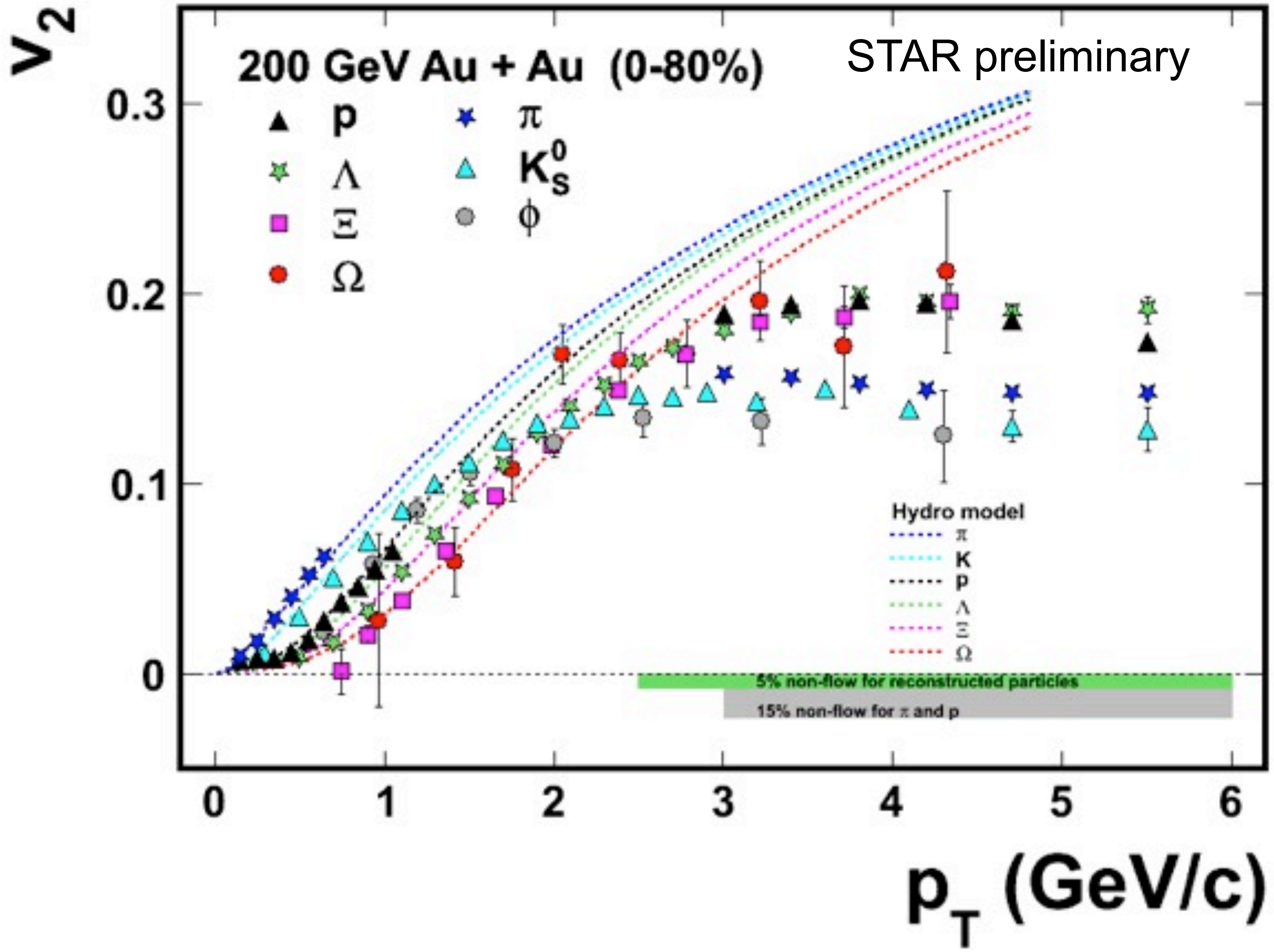
- Main TPC: Full azimuth, $|\eta|<1$
- (Multi-)strange hadrons (K^0_S, ϕ, Λ, Ξ, Ω, ...), Resonances

➡ Large acceptance

What have we learned at RHIC ?

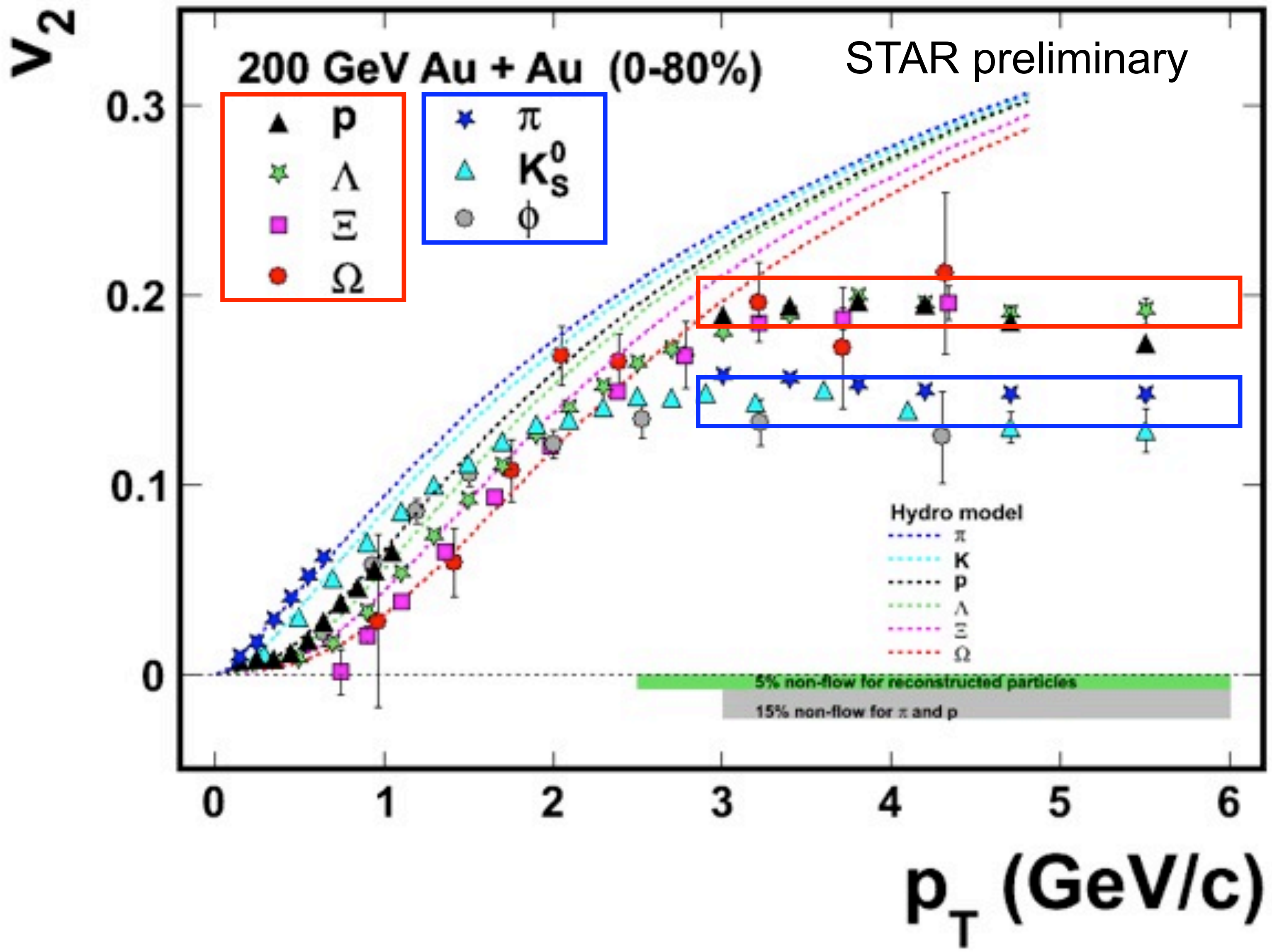
Success of ideal hydrodynamics

STAR: QM09, DNP09



- Ideal hydrodynamic models work for $p_T < 1$ GeV/c
  - ✓ Mass ordering of v_2, smaller v_2 for heavy hadrons → radial flow
  - ✓ need early thermalization, $\tau \sim 1$ fm/c
- What can we learn from higher p_T ?

Success of ideal hydrodynamics



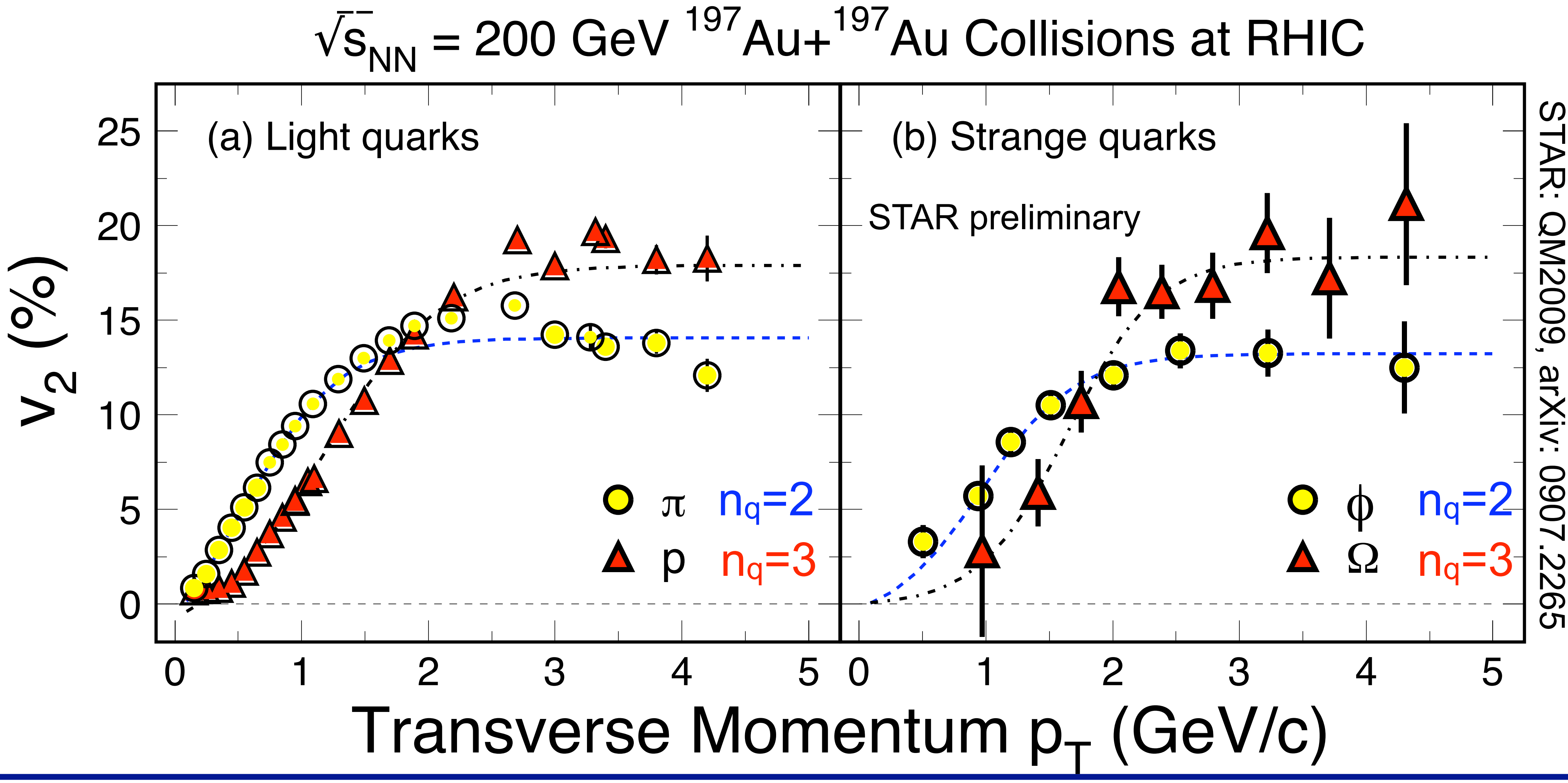
STAR: QM09, DNP09

Baryons

Mesons

- Ideal hydrodynamic models work for p_T < 1 GeV/c
  - ✓ Mass ordering of v_2, smaller v_2 for heavy hadrons → radial flow
  - ✓ need early thermalization, $\tau \sim 1$ fm/c
- What can we learn from higher p_T ?

Partonic collectivity



- Number of quark scaling among measured hadrons

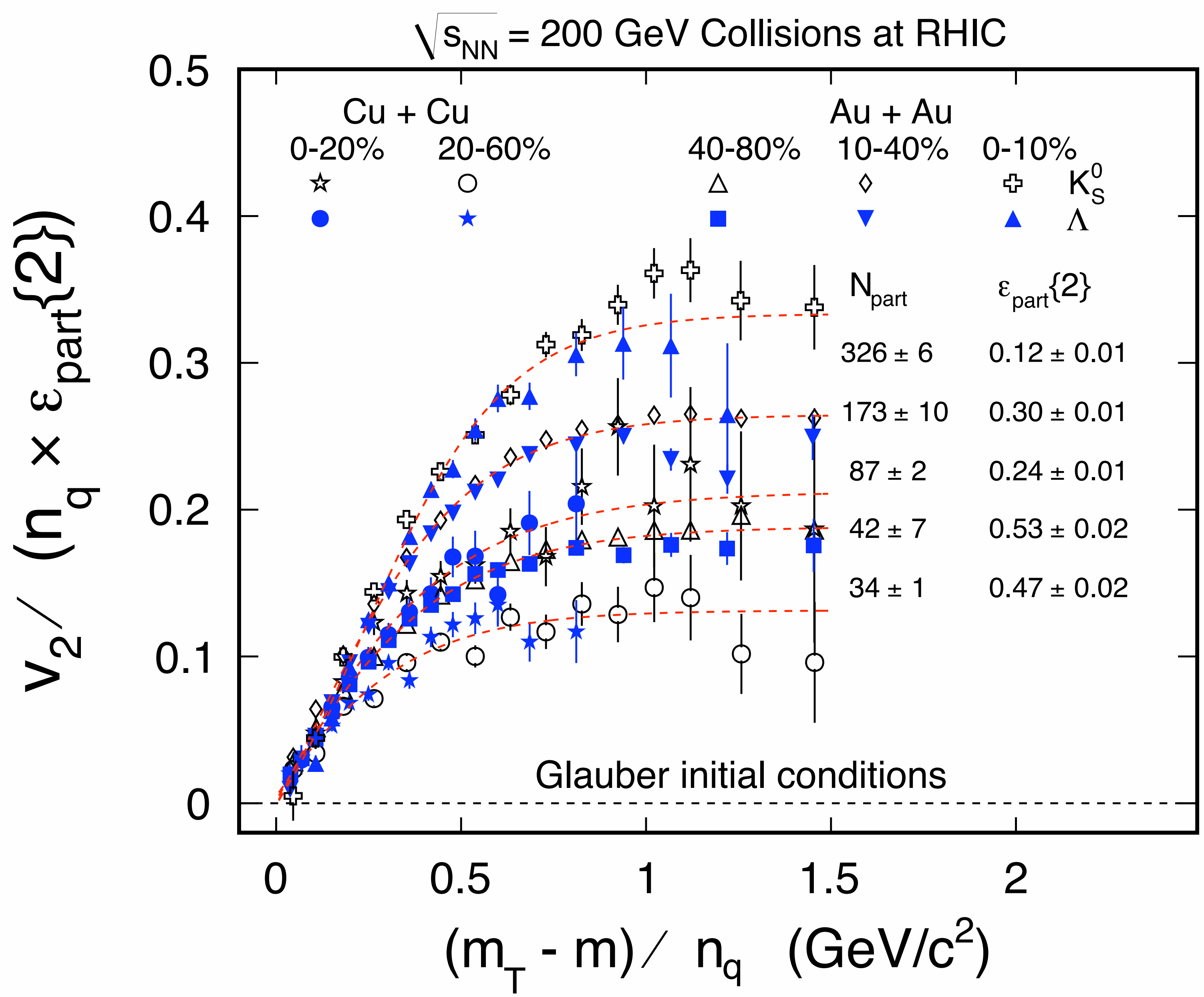
✓ v_2 scales by number of quarks for p_T > 2 GeV/c

✓ Confirmed for multi-strange hadrons; φ and Ω

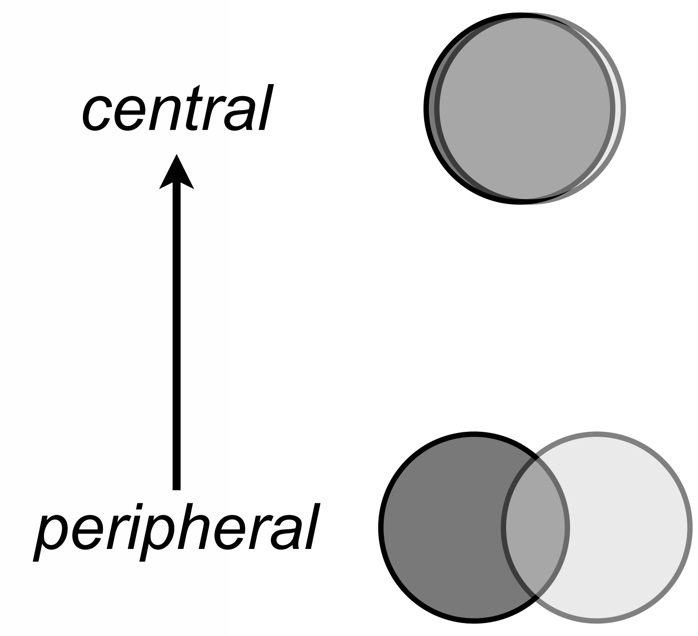
➡ Collectivity developed in the early partonic matter

➡ Deconfinement

Stronger flow in central collisions



Cu + Cu : STAR preliminary
Au + Au : PR**C77**, 054901 (2008)

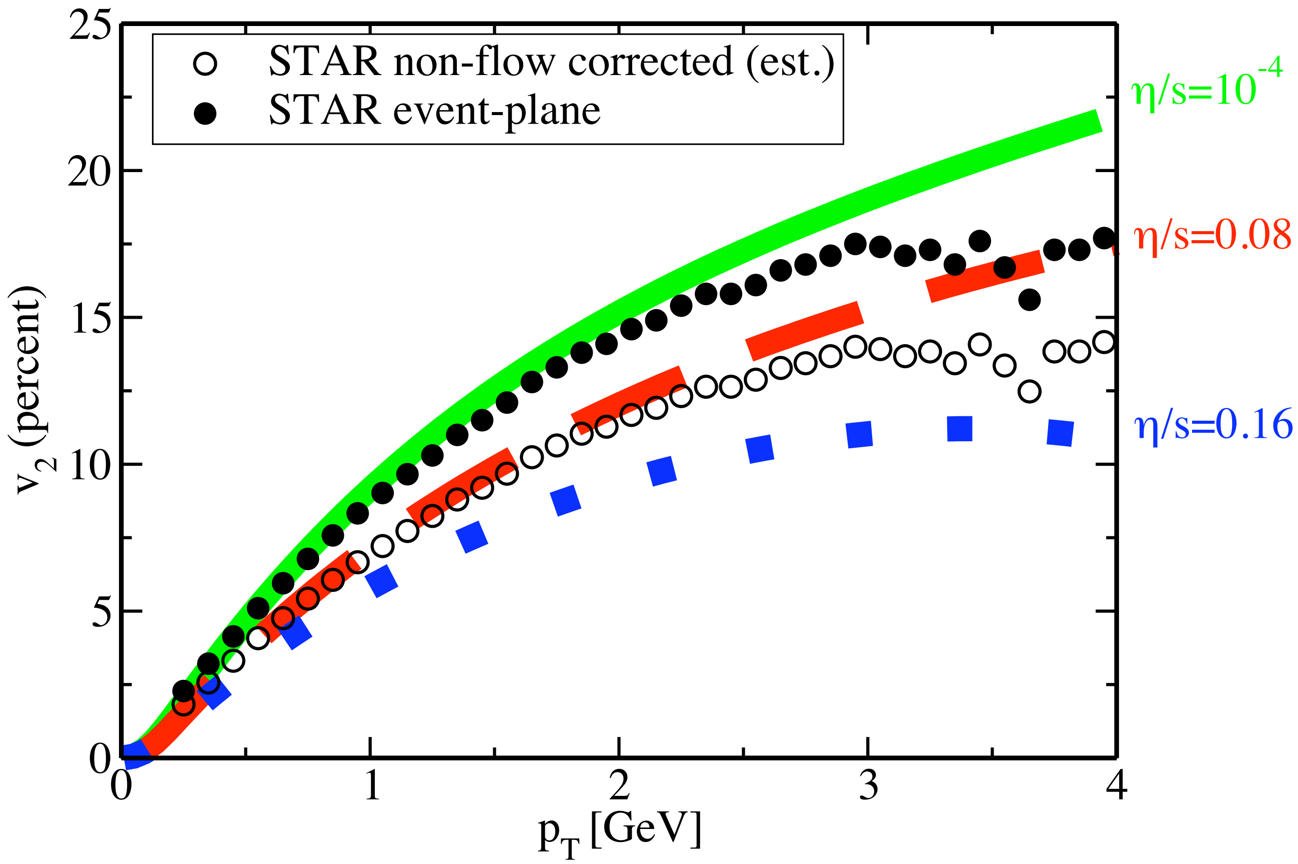


- Number of quark scaling holds for each centrality
- Stronger collectivity in central collisions

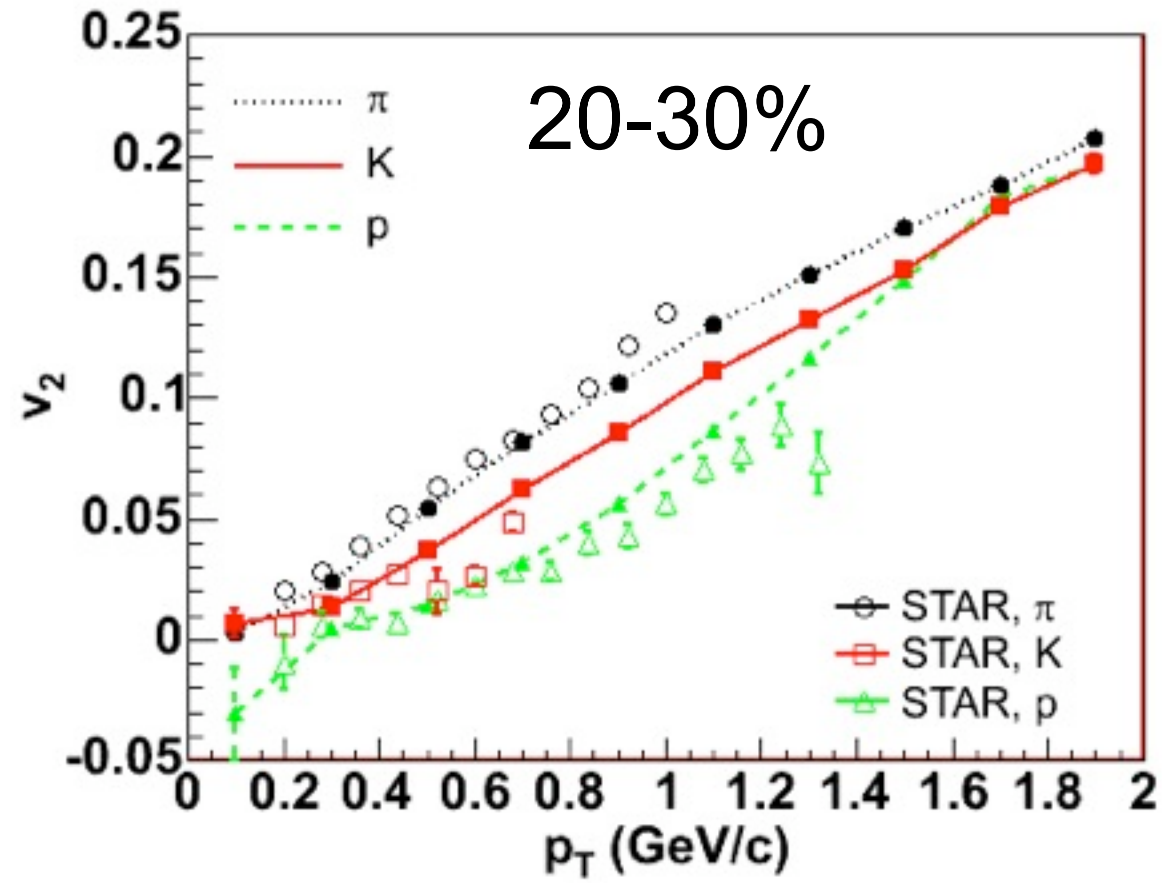
✓ Collectivity is driven by the eccentricity and system size

‘Viscosity’ corrections

M. Luzum and P. Romatschke, PRC**78**, 034915 (2008)



T. Hirano et al., PR**C77**, 044909 (2008)



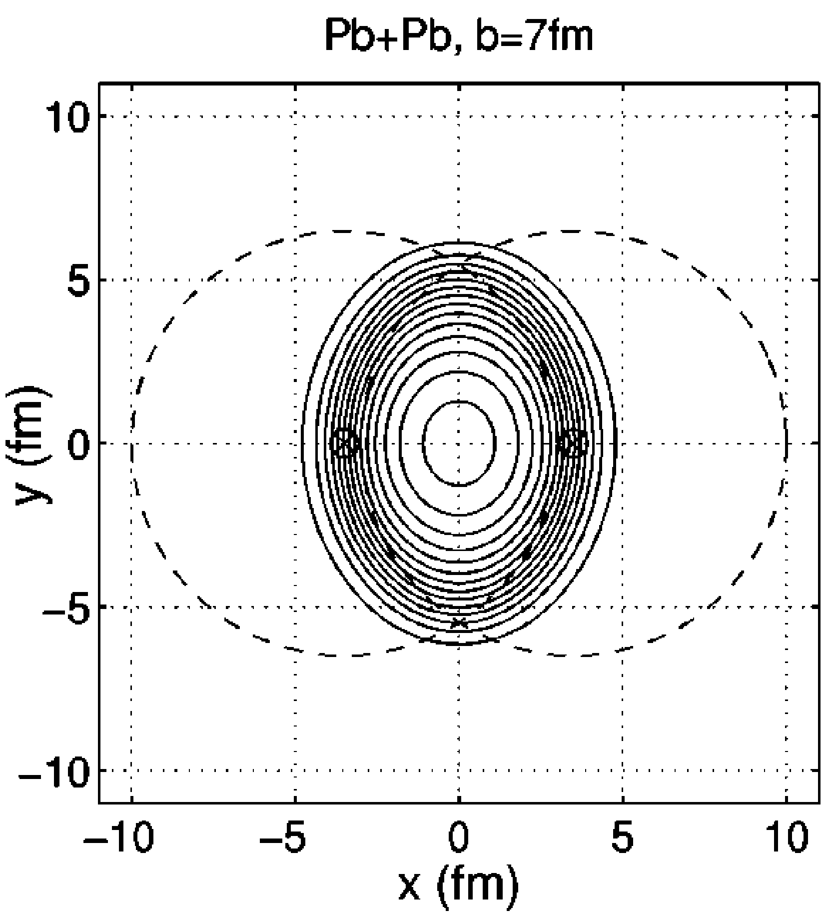
- Measured v_2 is sensitive to the viscosity corrections
  - ✓ prefer finite but small shear viscosity to entropy density ratio of medium
  - ➡ important constraint on the transport coefficients
  - ✓ Caveats: hadronic rescattering, initial conditions, EOS, ...

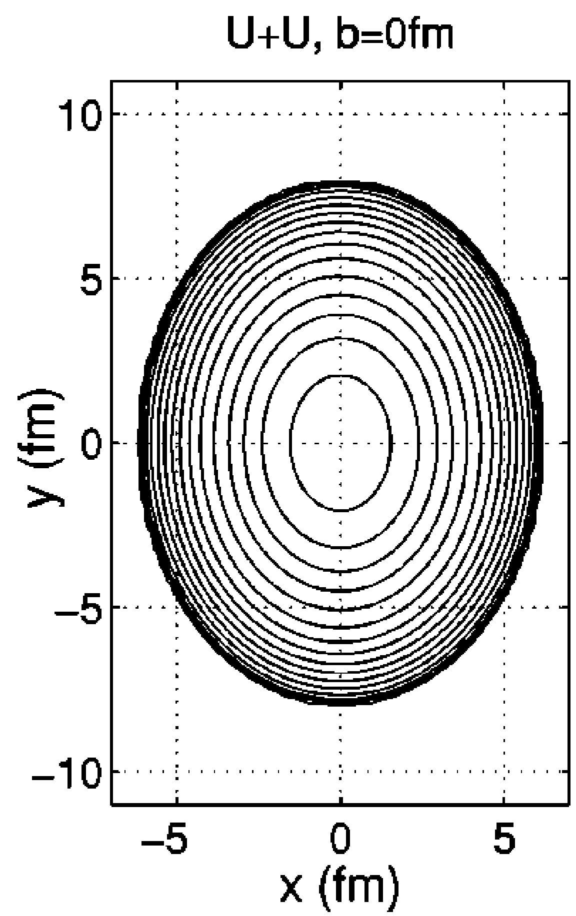
What can we learn from future v_2 measurements at RHIC ?

U + U collisions

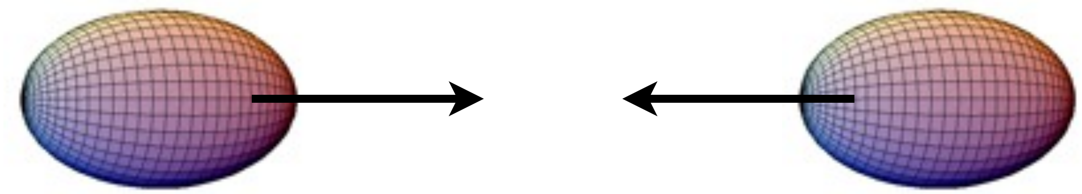
di-leptons

Why U + U collisions ?

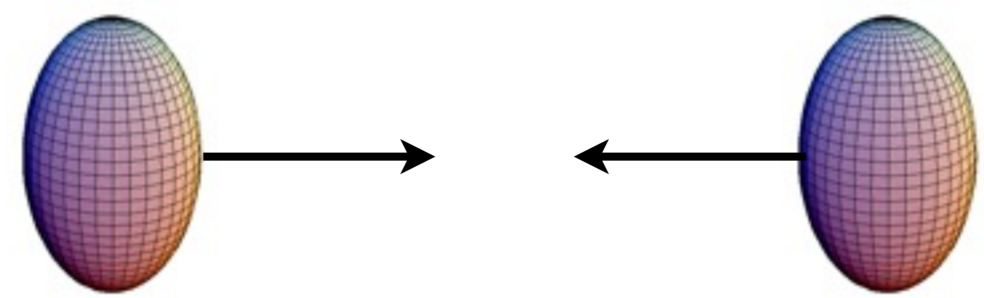




"tip-tip" collision
collision along the longest axis



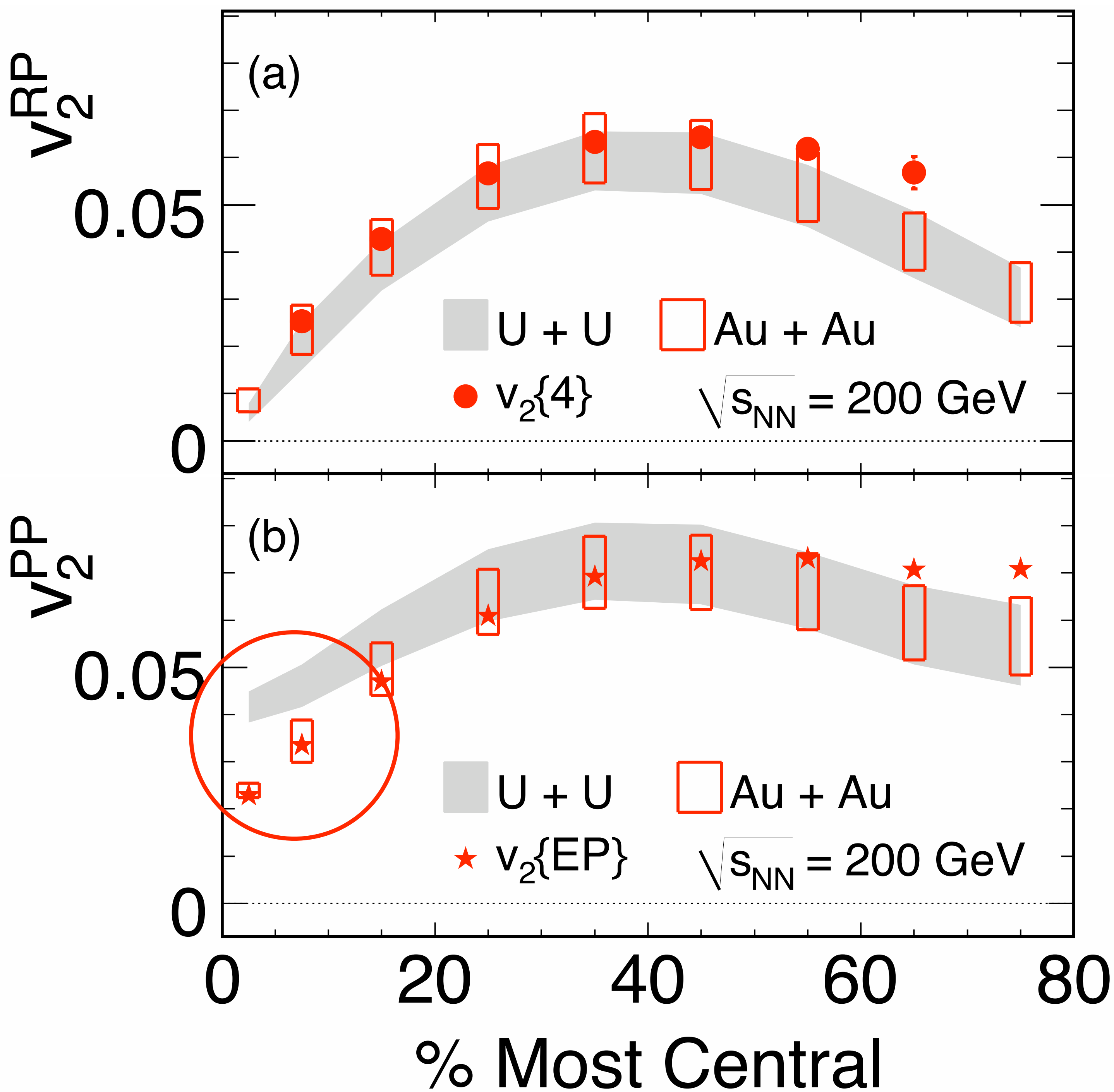
"body-body" collision
collision along the shortest axis



- U nucleus is heavier than Au, and naturally deformed
- Increase transverse number density & duration time
  - ✓ density increases ~35% in central "tip-tip" U + U compared to the spherical Au + Au C. Nepali et al., Phys. Rev. **C73**, 034911 (2006)
  - ✓ freeze-out occurs ~30% later in central "body-body" U + U than in Pb + Pb at b = 7 fm P. F. Kolb et al., Phys. Rev. **C62**, 054909 (2000)

Effect of deformation

H. M., B. Mohanty and N. Xu, PLB**679**, 440 (2009)

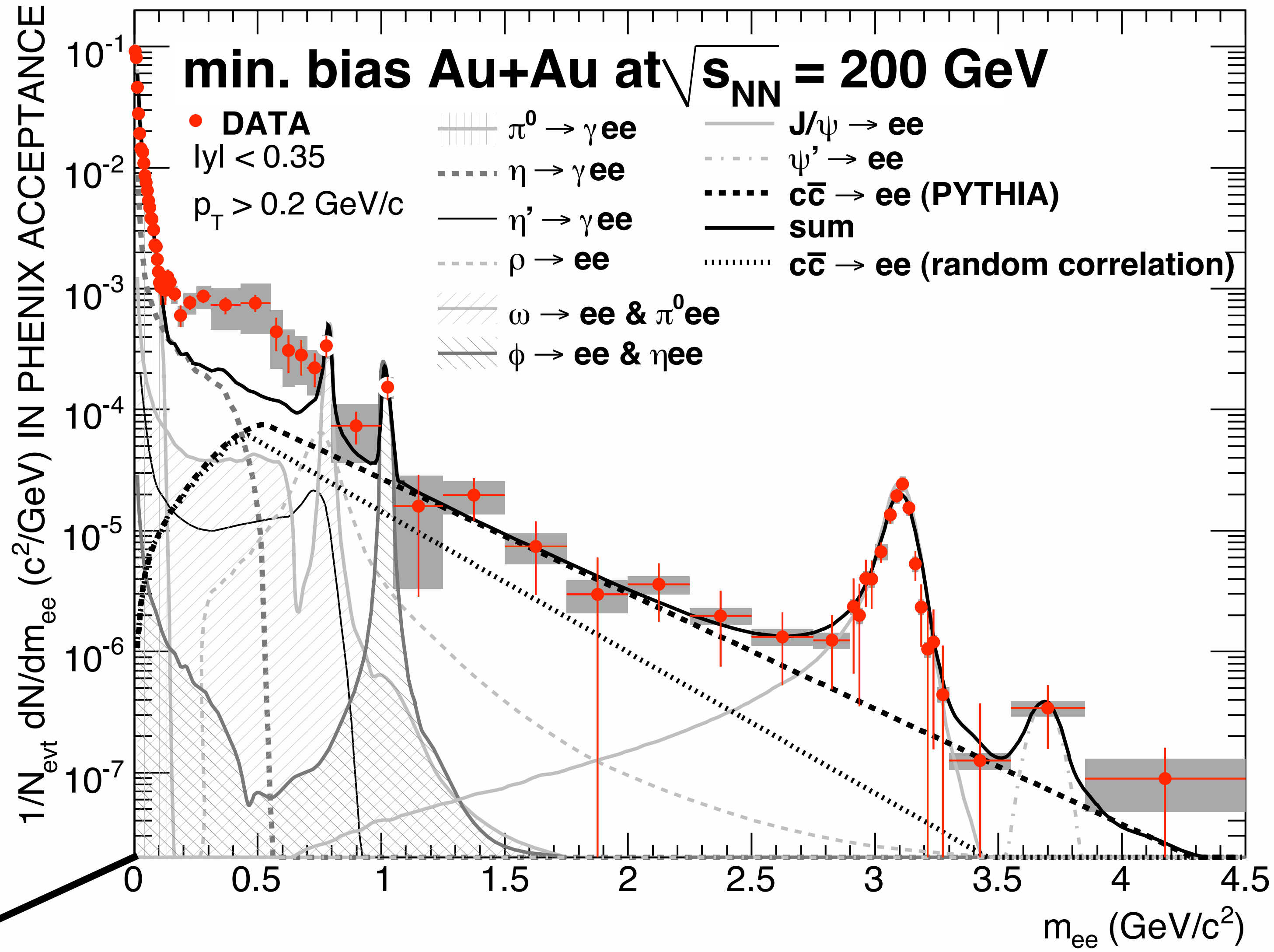


Results in U + U collisions are averaged over all possible orientations

- Increase v_2 with respect to the participant plane at most central
  - ✓ Due to the deformation of uranium
  - ✓ Deformation → larger geometrical anisotropy → larger v_2
  - ✓ Caveats
    - Collisions dynamics need to be taken into account
- U + U collisions will be possible at RHIC in 2012

Di-leptons

PHENIX: arXiv:0706.0304



p_T, centrality

- Di-lepton v_2 measurements (vs mass, p_T, centrality)

✓ Direct radiation from the medium, no strong interactions

➡ Probe to the deconfinement, thermalization

- PHENIX: HBD, STAR: Full barrel TOF

Conclusions

- Elliptic flow has played a major role in understanding the properties of the medium created at RHIC
  - ✓ Hydrodynamical models → radial flow, early thermalization
  - ✓ Partonic collectivity → deconfinement
  - ✓ Stronger collectivity in central collisions → $v_2 = \varepsilon \times f(\text{system size})$
  - ✓ Provide important constraint on transport coefficients
- Future v_2 measurements would shed more light on the collision dynamics in heavy ion collisions
  - ✓ U + U collisions, v_2 for di-leptons
- Many other important measurements
  - ✓ heavy flavors (charm & bottom quarks), direct (thermal) photon
  - ✓ Other harmonics (v_1, v_4 ...), v_2 fluctuation